PROGRESS IN Nb_3Al AND Bi:2212 FOR ACCELERATOR APPLICATIONS

M.D. Sumption and E.W. Collings, F. BUTA
MSE, The Ohio State University

E. Gregory and L. Motowidlo
IGC Advanced Superconductors

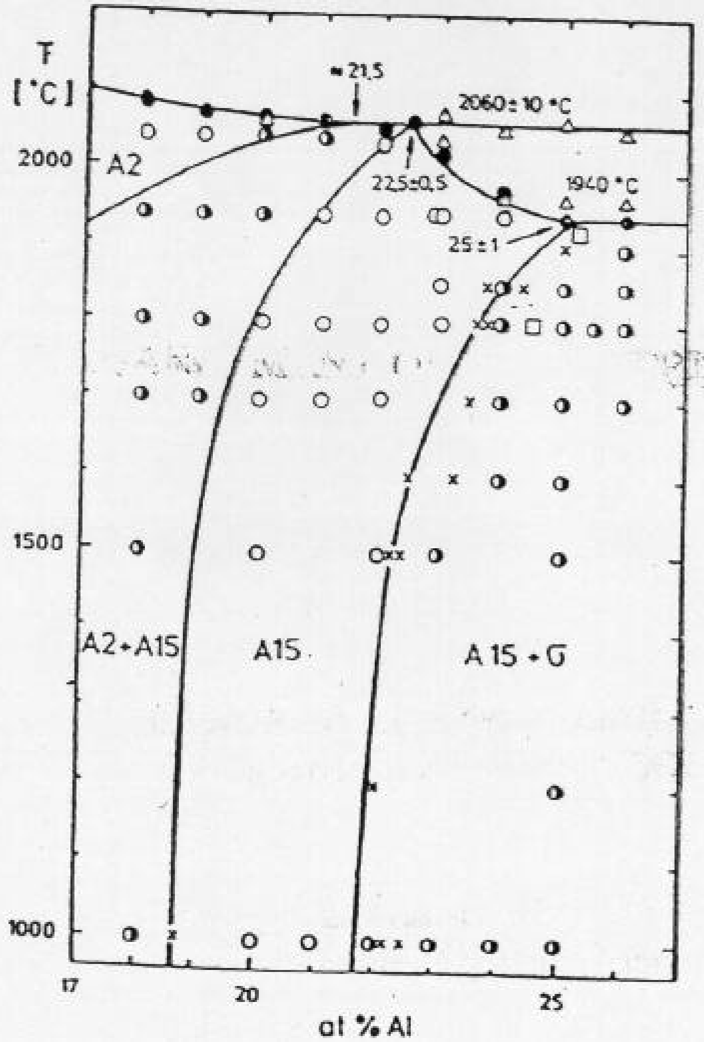
R. Scanlan
Lawrence Berkeley National Laboratories

M. Tomsic
Plastronics

Presented at the workshop for

Magnets for a very Large Hadron Collider
Port Jefferson, NY, USA
16-18 Nov., 1998

THE Nb-Al EQUILIBRIUM PHASE DIAGRAM



J.L. Jorda, 1981.

- Maximum T_c and $H_{c2}(0)$ occur at stoichiometric Nb_3Al.
- This occurs (for the equilibrium phase diagram) only at 1940°C, at one point in the A15-phase field.
- Stoichiometric A15 which is metastable at low temperatures can be fabricated.
- All practical (low temperature, i.e. < 1000 C) routes have so far failed to achieve optimal T_c (and thus H_{c2} and J_c).

INTRODUCTION

The processing of superconducting Nb_3Al strand may be regarded as a two-step operation.

Step-1 has to do with the numerous ways of producing a microscale assembly of the elemental ingredients, the "precursor", by for example the methods of:
powder metallurgy, clad chip extrusion,
jelly roll, modified jelly roll, rod-in-tube, and so on.

Step-2 is the heat treatment (HT) required to convert the precursor into the desired A15 phase. With certain obvious exceptions, any of the precursors may be HT in one of two possible ways:

(i) **LT-SD**: low temperature (<1000°C) partial solid-state diffusion,

(ii) **MQ-OHT**: melt quenching (MQ) followed by a moderate ordering heat treatment (OHT).

LT-SD processing of strand (for fusion) yields a material that is superior to the best Nb_3Sn only in fields below about 12-13 T.

MQ-OHT processing is the only feasible route towards strand suitable for high-field magnet applications.

The MQ segment may use: (i) electron-beam, (ii) CO_2 laser, or (iii) resistive (i.e. "ohmic") heating.

"STEP-1", PRECURSOR FABRICATION

In recent years the less successful **Step-1** processes have been winnowed out leaving just two favored methods for long length processing:

(1) rod-in-tube (RIT)

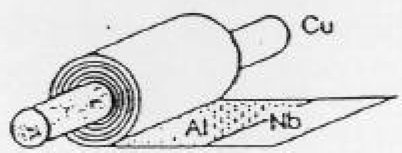
(2) jelly roll (JR)

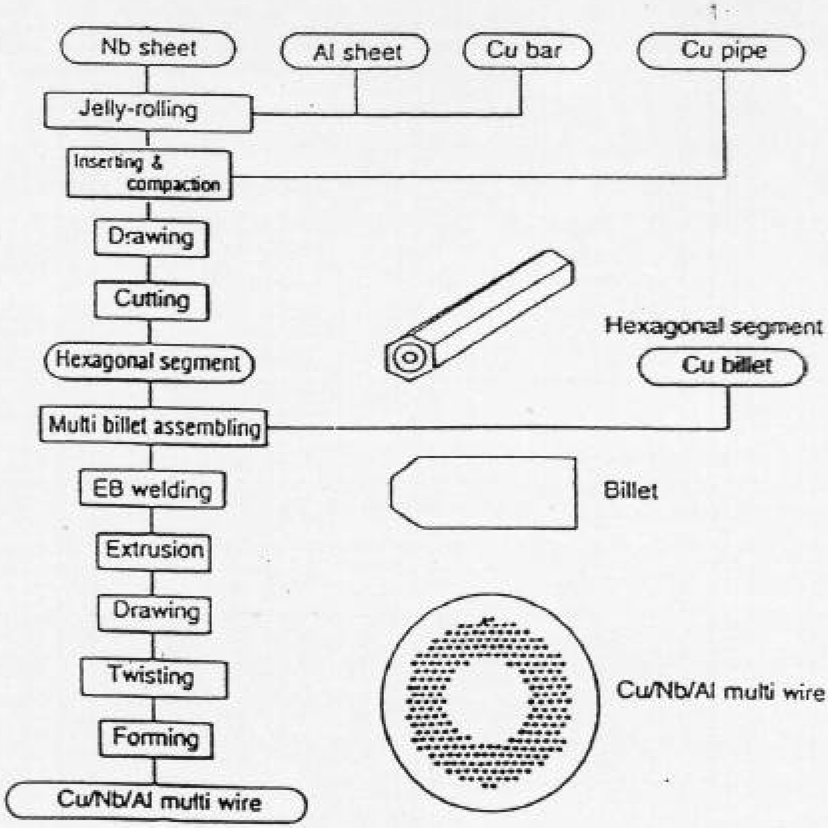
We have produced both of these types of precursor strand.

(1) (RIT): The starting point for the rod-in-tube material was a coaxial arrangement of Nb and Al tubes surrounding a Nb rod; this we referred to as a "modified rod-in-tube" or MRT process.

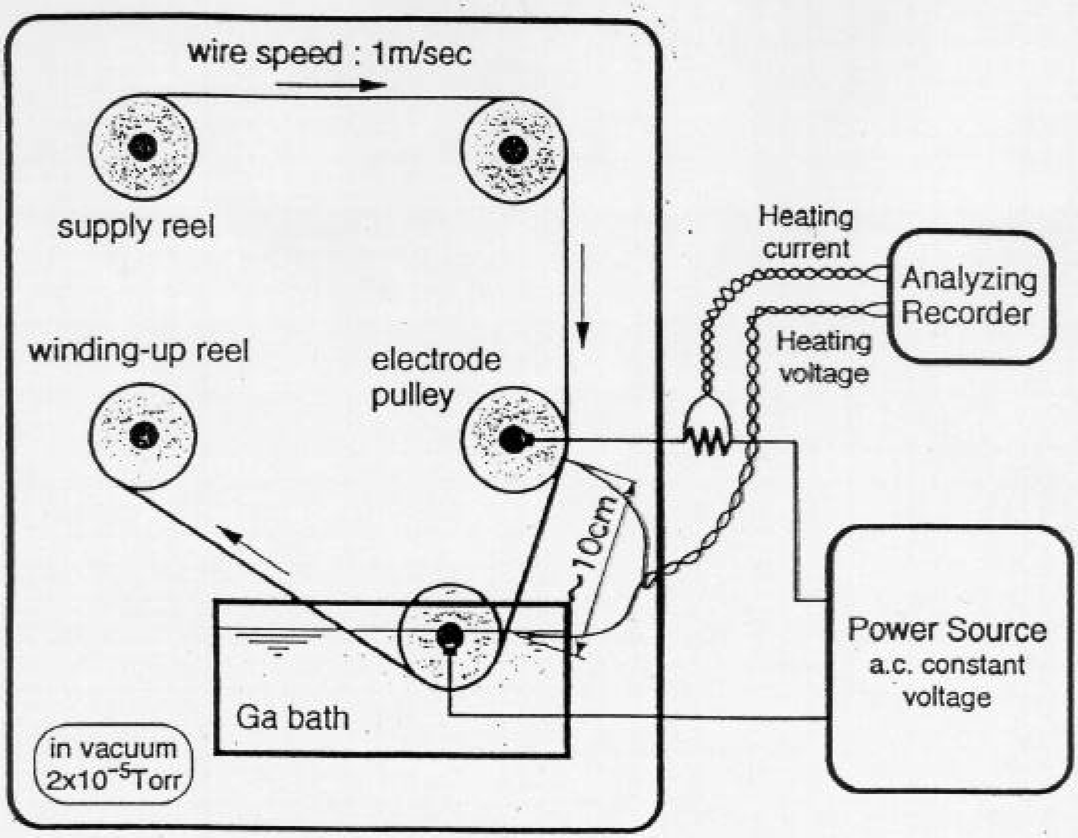
(2) (JR): The starting billet for the jelly roll (JR) strand was assembled by wrapping foils of Nb (0.762 mm^t) and Al (0.0254 mm^t) around a Nb core of diameter 3.175 mm.

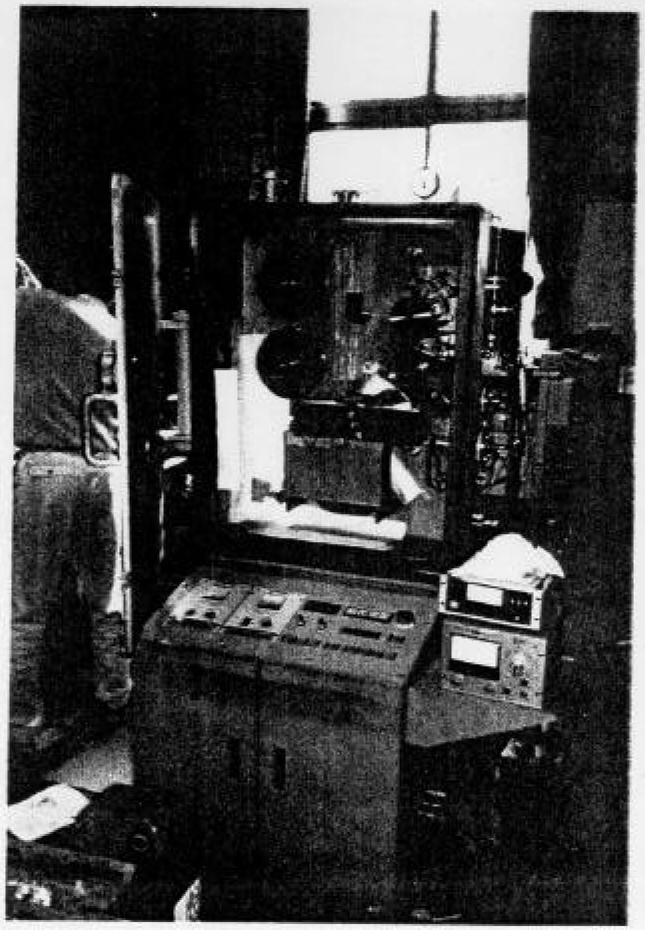
THE JELLY-ROLL ASSEMBLY METHOD

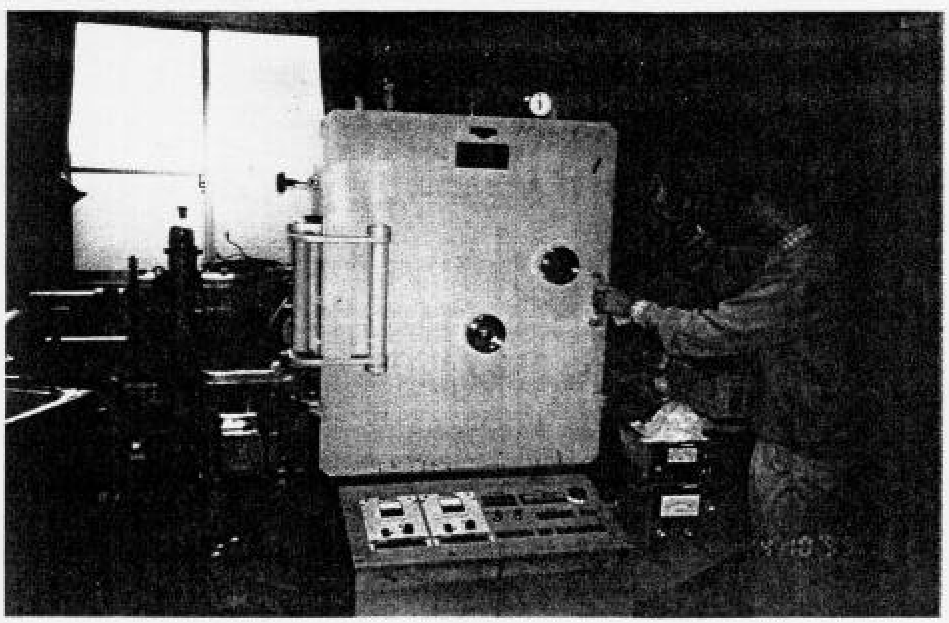




APPARATUS FOR OHMIC HEATING
(Solid-State Quenching)







Developments in Nb_3Al: NRIM/HITACHI

Length achievements: Two main processing methods for precursor manufacture: JR + HE + drawing, vs Rod-In-Tube (Mg doped)+ cassette rolling/drawing. Cassette drawing gives typical lengths of *300 m*. Hydrostatic extrusion is giving lengths of up to *1 km*.

Deformation and Cabling (After Primary reaction – bcc phase)

Winding mode: Semi-react-and wind

It is possible to draw slightly (using cassette roller dies) the as-quenched wire (bcc) by a factor of about 2 in radius (0.9 mm to 0.48 mm). This can be done with negligible difference in SC properties.

It is possible to roll the as quenched wire as well – aspect ratios of 15 have been seen

Small prototype cables have been made – 9 strands, with good I_c retention

Stabilizer: Some attempts to put on a stabilizer have been attempted – both in a prototype cable and around individual strands. Short reports of limited success.

Secondary Reaction HT temperatures: 700-800 °C for the secondary reaction, slow and forgiving ramp up and ramp down, reasonable HT times (a few hours to 50 hours).

Other Magnet compatibility Issues

Flux jump stability --
Nb matrix makes this worse – non-SC barrier materials are needed.

d_{eff}: 25-60 μm

Strain tolerance: quite good

B_{c2} Values
NbAl: 25-27 T
NbAlGe: 34-39.4 T (no lengths reported)

J_c Values
NbAl: 200 A/mm^2 at 21 T
NbAlGe: 100 A/mm^2 15-25 T (no lengths reported) – ductility problems.

ADVANCES

IN

MULTIFILAMENTARY Nb_3Al STRAND PROCESSING

AT

THE LABORATORIES FOR APPLIED SUPERCONDUCTIVITY AND MAGNETISM

DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING

THE OHIO STATE UNIVERSITY

THE SHORT SAMPLE APPARATUS

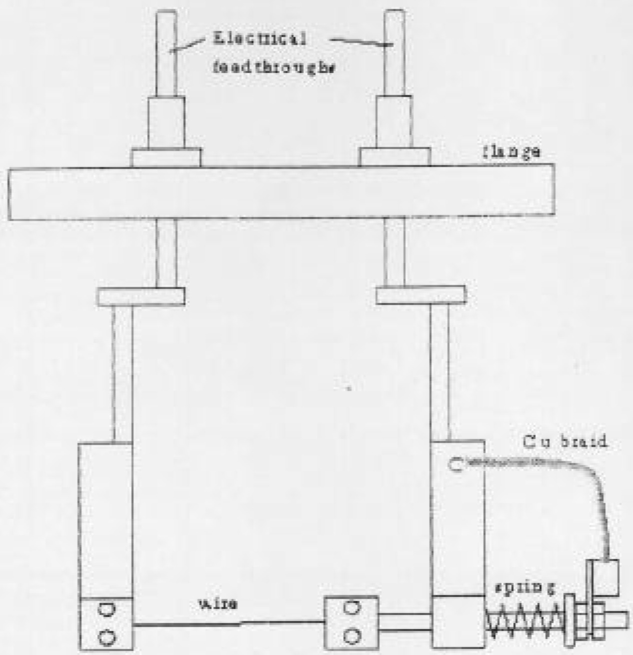
The short sample apparatus derived from pulse heating equipment presently in use at Yamaguchi University.

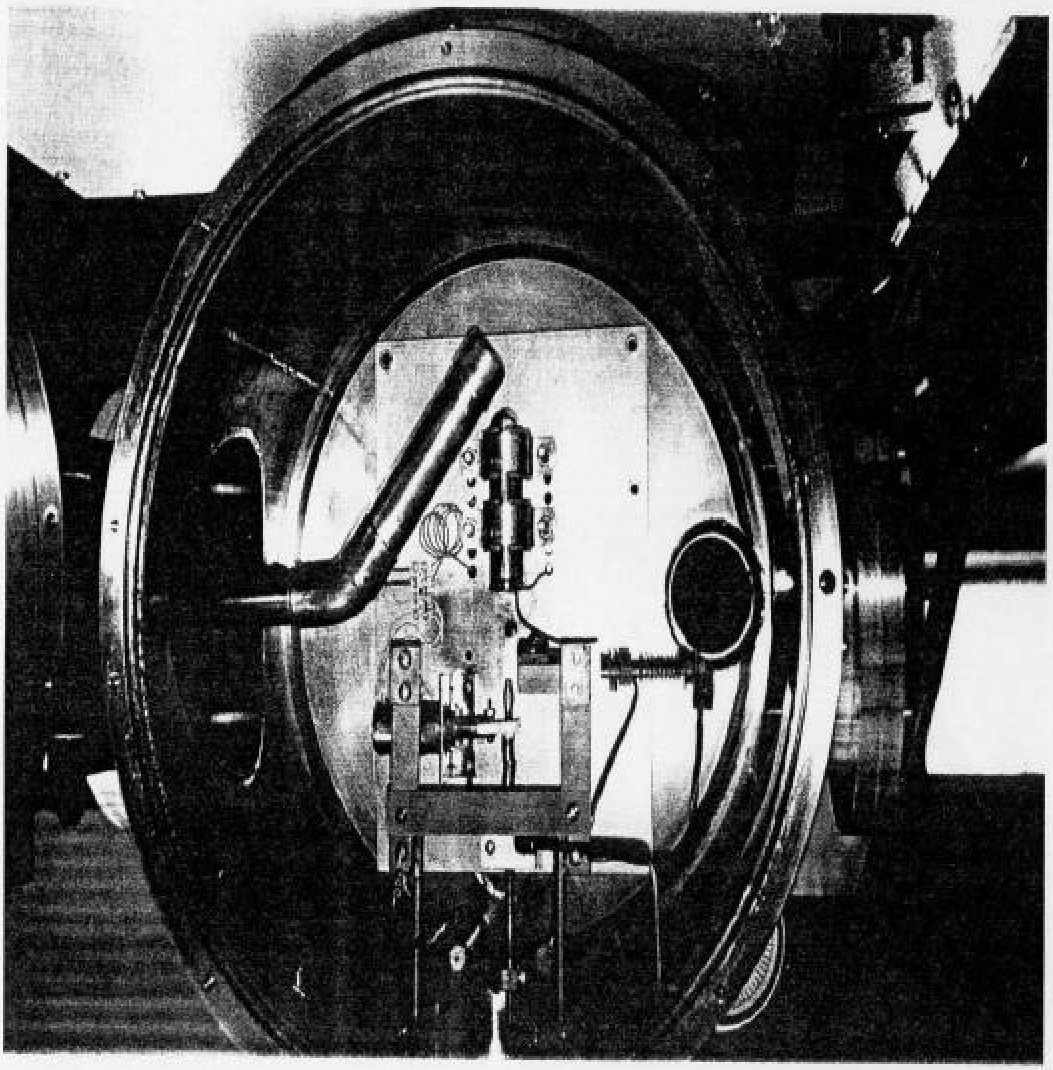
Built around a modified Bühler splat quencher, the turbopumped (Alcatel 5150) sample chamber achieved an ultimate vacuum of $2x10^{-6}$ torr.

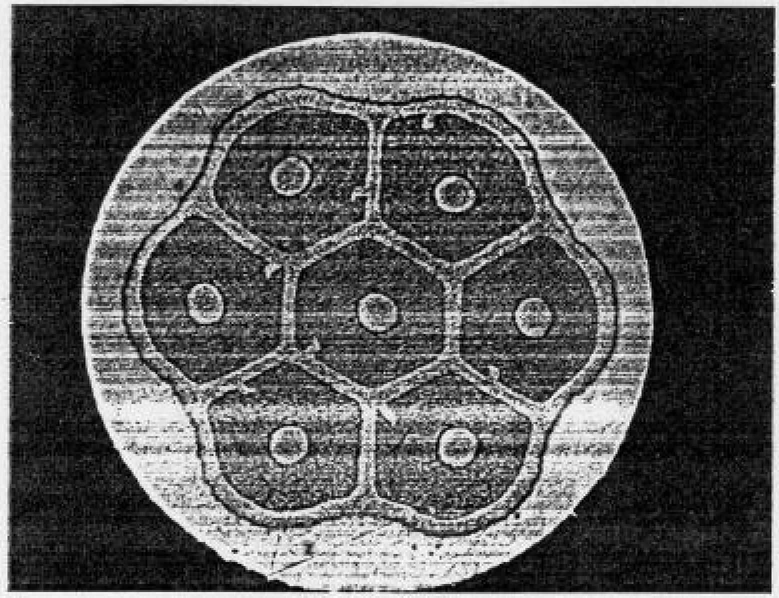
The spring tensioned Nb-clad sample wire is heated by a pulse of alternating current while its temperature is monitored by a photodiode -- which had been calibrated using a disappearing filament pyrometer (Micro-Therm, Pyrometer Instruments Co.), due attention being paid to the emissivity of Nb and the transmittance of the glass windows.

The voltage generated by the photodiode and that across the current shunt were measured by a pair of HP 3457A multimeters connected to a 486-PC using a GPIB interface. A program in LabView was written to operate the multimeters, read the data, make calculations, display and save the data to disk.

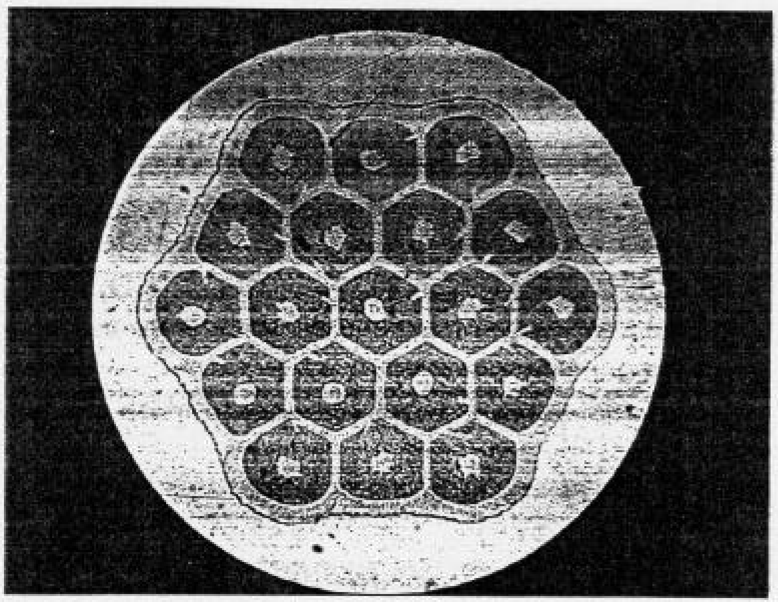
The minimum sampling time for the DC voltage (photodiode) measurement is 0.02 s. Using a stored calibration the LabView program converted the photovoltage to temperature and stopped the sample current when the desired temperature was reached.


Electrical
feedthroughs
flange
Cu braid
spring
wire

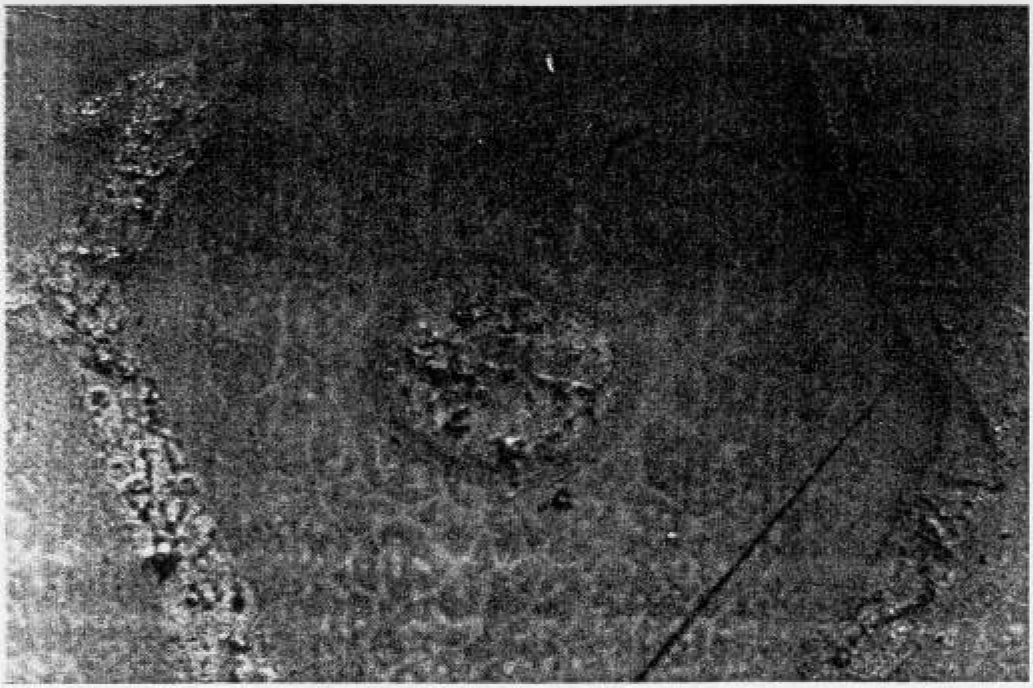




7-stack jelly roll, originally 50X

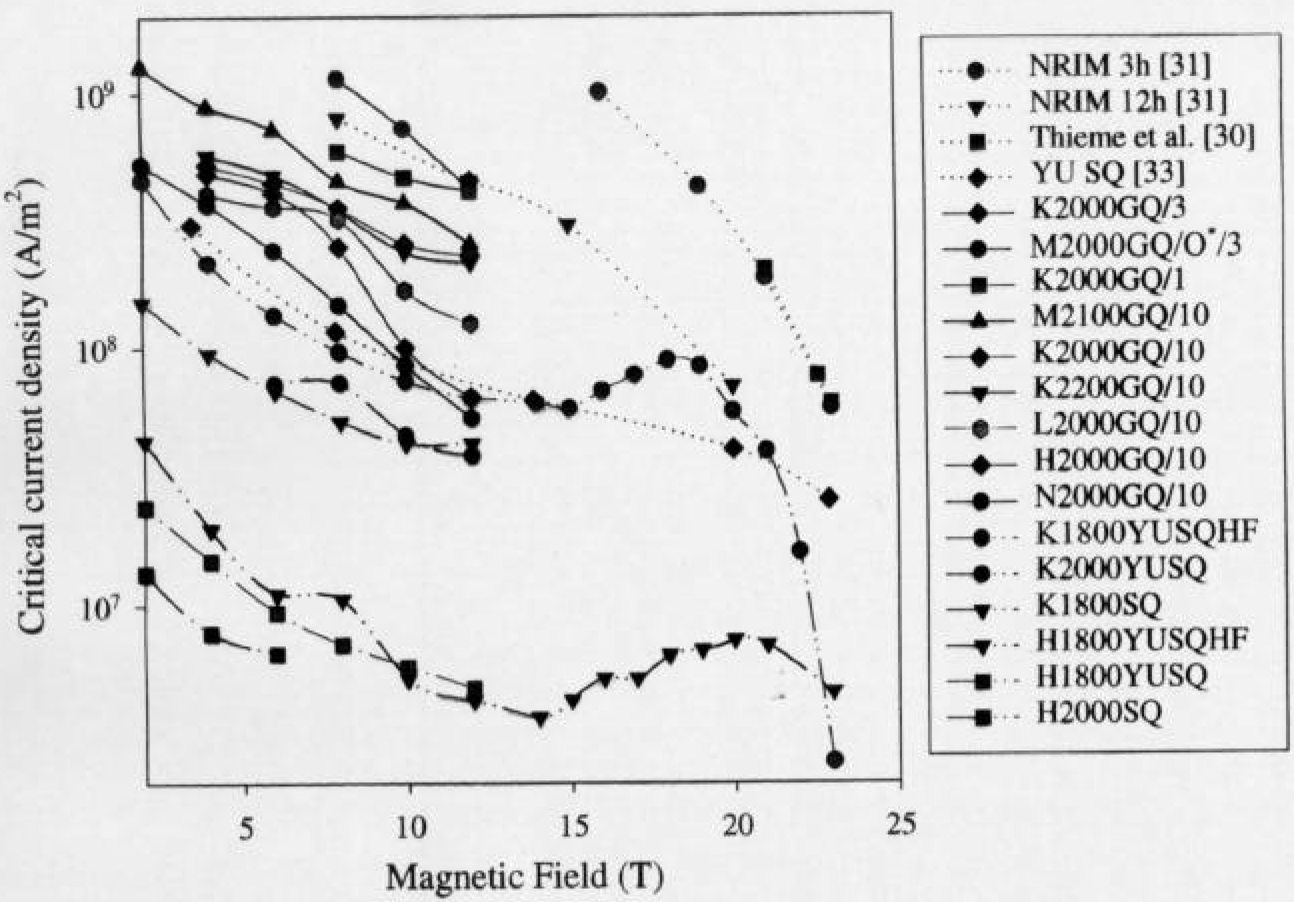


19-stack jelly roll, originally 50X



L-Series Strand (Nb:Al = 3:1) Ga-quenched from 2000°C

K-Series Strand (Nb:Al = 5:1) Ga-quenched from 2000°C



Critical current density (A/m²)
10⁹
10⁸
10⁷
5
10
15
20
25
Magnetic Field (T)
NRIM 3h [31]
NRIM 12h [31]
Thieme et al. [30]
YU SQ [33]
K2000GQ/3
M2000GQ/O*/3
K2000GQ/1
M2100GQ/10
K2000GQ/10
K2200GQ/10
L2000GQ/10
H2000GQ/10
N2000GQ/10
K1800YUSQHF
K2000YUSQ
K1800SQ
H1800YUSQHF
H1800YUSQ
H2000SQ

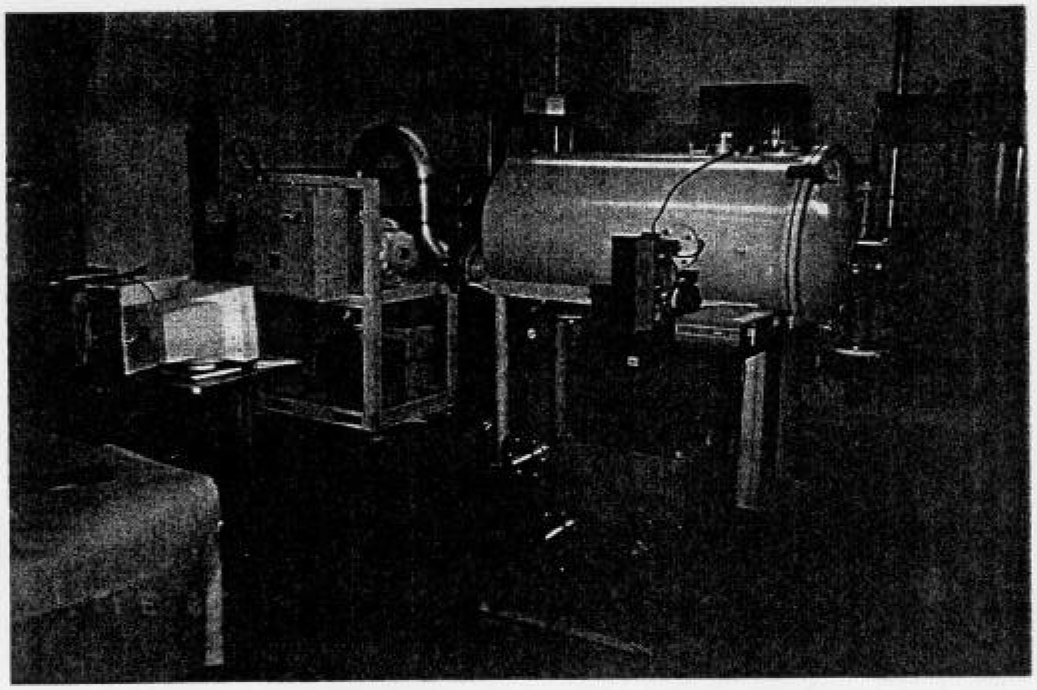
LONG SAMPLE REEL-TO-REEL MELT-QUENCH PROCESSING EQUIPMENT

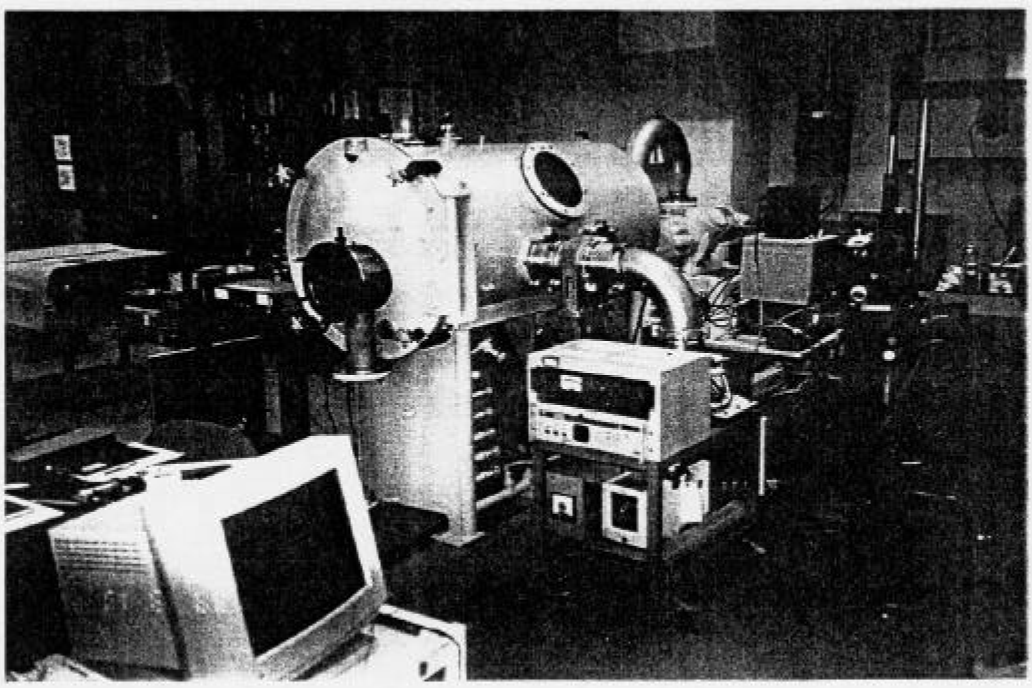
High vacuum ohmically heated reel-to-reel equipment based on the NRIM design was constructed.

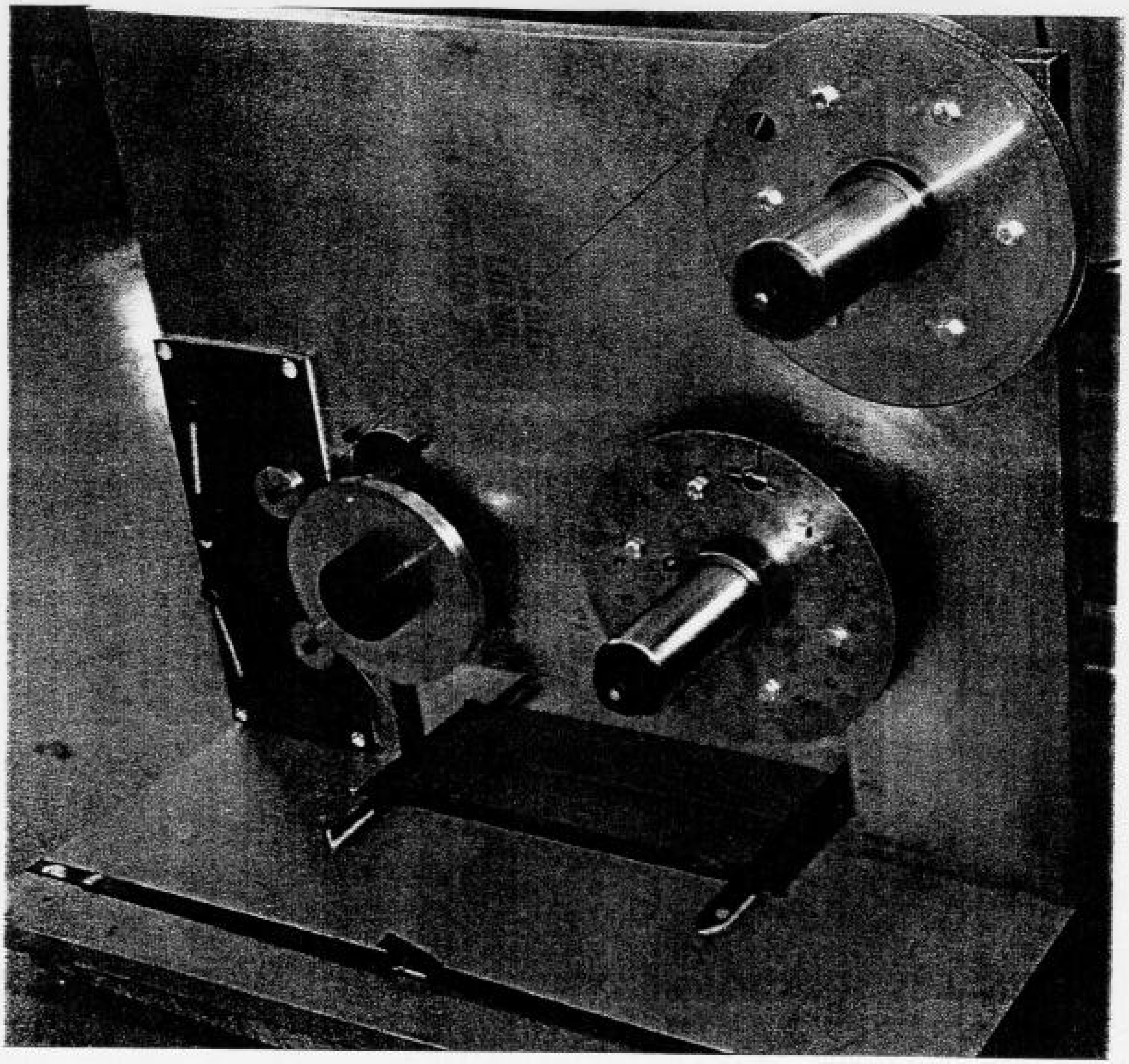
The vacuum chamber has a wide front access and is large enough (720 liter) to accommodate equipment for the processing of very long lengths of wire.

A Rootes blower system is coupled to the rear of the chamber through 15 cm valving and tubing; the 5 HP blower (Leybold-Heraeus WAU1001) and its 10 HP forepump (SV280) are able to bring the chamber pressure down to the 14 mtorr range in about 5 minutes.

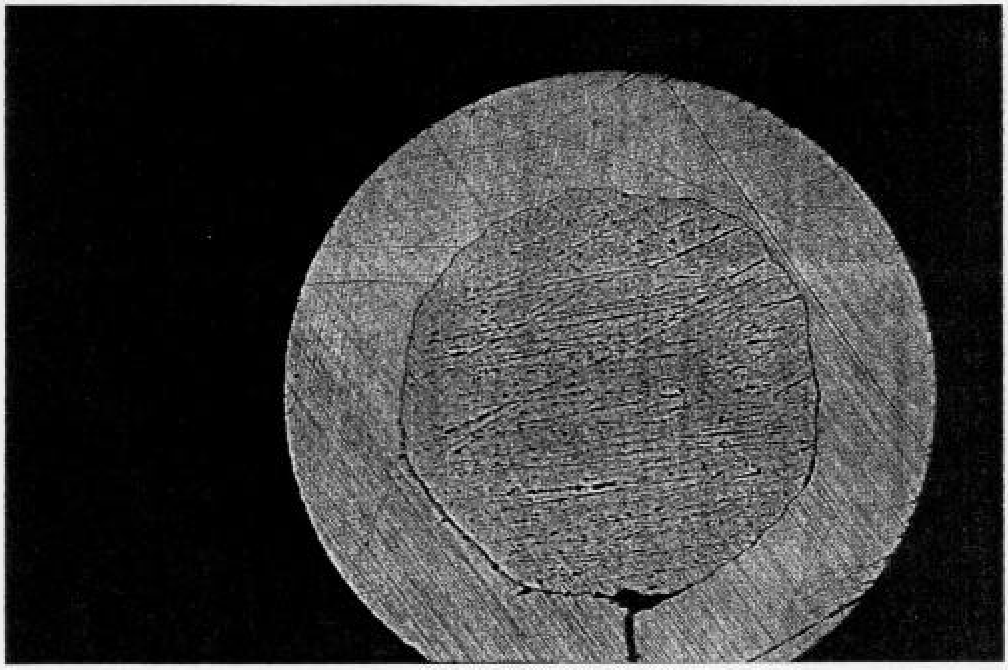
A turbopump system (Pfeiffer-Balzers TPH520M with DUO016B forepump) coupled into the side of the chamber also through 15 cm valving and tubing can take over from the blower (when valved off) and reduce the chamber pressure to $2x10^{-6}$ torr without the aid of nitrogen trapping.



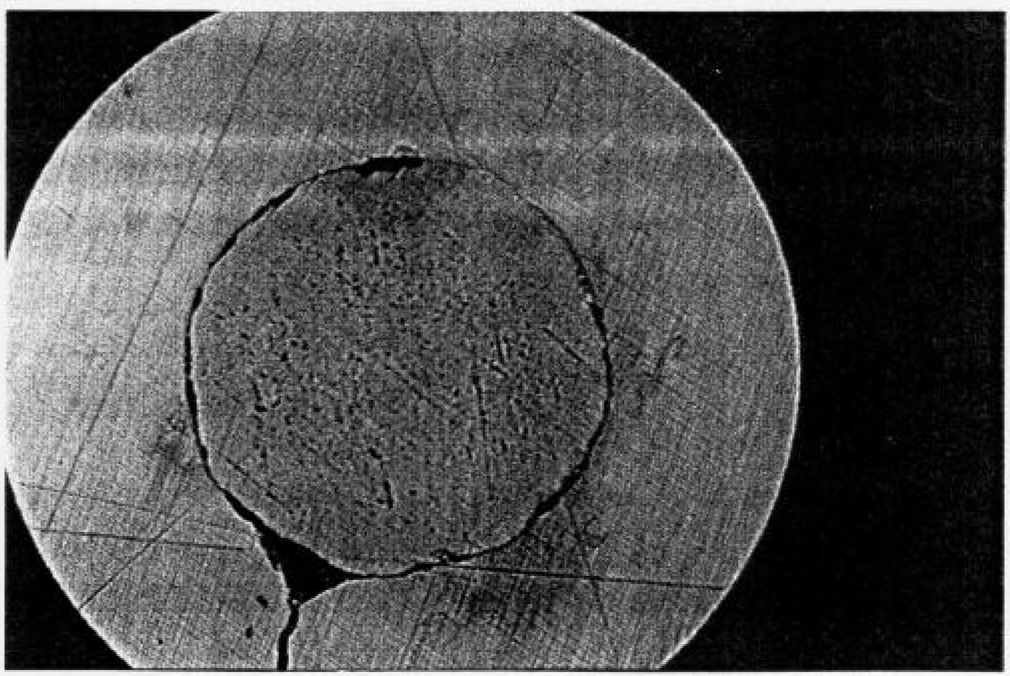




Reel-to-Reel Ohmic Heating and Quenching Assembly



(01)



(04,

DESIGN, PROCESSING, AND PROPERTIES OF Bi:2212/Ag RUTHERFORD CABLES

E.W. Collings and M.D. Sumption

Department of Materials Science and Engineering
The Ohio State University
Columbus, OH 43210, U.S.A.

R.M. Scanlan and D.R. Dietderich

Superconducting Magnet Group
Lawrence Berkeley National Laboratory
Berkeley, CA 94707, U.S.A.

L.R. Motowidlo and R.S. Sokolowski

IGC Advanced Superconductors
Waterbury, CT 06704, U.S.A.

Y. Aoki and T. Hasegawa

Showa Electric Wire and Cable Co
Kawasaki, Kanagawa, Japan 210

SUMMARY

A research & development collaboration was established between:

a *U.S. National Laboratory (LBNL)*
a *University (OSU)*
and *two SC manufacturing companies (IGC, SEWC)*

During the course of the R&D the feasibility of winding a core-type Rutherford cable with Bi:2212/Ag strand, with good handleability and with acceptable current carrying capacity, was demonstrated.

Estimates were made of the extent of I_c degradation that results from winding-induced damage and poisoning from the Nichrome-80 core if unprotected by a suitable oxide coating. Ways of reducing degradation have been identified.

The results of model-cable AC loss measurements, extrapolated to the dimensions of an LHC-inner cable, yielded an effective FO ICR, $R_{\perp,eff.,LHC}$, of 10-13 $\mu\Omega$ which is close to a stated LHC target of 15 $\mu\Omega$.

STRUCTURE OF THE PROGRAM

A collaborative program was initiated to produce a core-reinforced Rutherford cable with acceptable current-carrying and AC-loss properties during which the following activities took place:

(1) Cable winding techniques were developed, and winding performed, at the Lawrence Berkeley National Laboratory (LBNL)

(2) Core selection, strand degradation (mechanical,chemical, and thermal-shock) studies, and special low-AC-loss cable design, took place at The Ohio State University (OSU)

(3) AC loss measurements were performed by OSU at facilities operated by the University of Twente (UoT), Netherlands

(4) Reaction heat treatment (RHT) optimization, cable RHT, cable degradation (mechanical and chemical) studies, and I_c measurements were performed at IGC Advanced Superconductors (IGC-AS)

(5) A special study of core-induced poisoning of short samples of cable was carried out at the Showa Electric Wire and Cable Co (SEWC).

INTRODUCTION

Future generations of very high energy synchrotron-type hadron accelerators will require dipole magnetic fields higher than those presently available with NbTi even when operating at 2 K.

For this reason experimental Nb_3Sn dipoles have been fabricated and tested and developments in Nb_3Al and HTSC Bi:2212 for future magnet applications are under way.

These advanced high field materials are all more-or-less brittle, a property that necessitates the use of:

(1) wind-and-react magnet fabrication technology
(2) the protection of the windings against in-service stresses.

Eventually new magnet and cable designs may be required for stress protection, especially of HTSC-based cables.

But for the time being it was decided to retain the conventional Rutherford cable configuration and to investigate for the first time whether such cables could be even wound with Bi:2212/Ag strand, and if so to measure some of their basic properties.

Following a successful experience with Nb_3Sn cable the HTSC cable design included a central core.

STRAND PROPERTIES

Three types of 0.81 mm diam. pure-Ag-sheathed strand were produced by IGC-AS:

(1) 84 fils., Ag-Zr matrix (No.251), (2) 90 fils., Ag matrix (No.320), and (3) 305 fils., Ag-Al matrix (No.380)
The four RHTs (HT1-HT4) used were slight modifications of the flowing-oxygen method of Hellstrom *et al.*

In a search for substrate-induced poisoning, strands were sandwiched between pairs of metal strips -- Haynes 230, Nichrome-80 (NC80), Nichrome-60 (NC60), and Ni, and given an RHT along with controls strands.

Although Haynes 230, NC60 and Ni were responsible for degradations in I_c, NC80 produced no significant effect. Partly for this reason NC80 was selected as core material for the Rutherford cables to be wound in this program.

We note, however, that the subsequent development of an improved heat treatment, HT4, has yielded a strand with a higher $I_{c,4.2K,self\,field}$ which more clearly reveals the effects of poisoning.

In tests of thermal-shock resistance a strand was cycled in various ways between RT and 4.2 K. The absence of thermal-shock-induced degradation in this case is ascribed to the presence the Ag-Al interfilamentary matrix.

CABLE PROPERTIES -- I

Critical Current, Further Poisoning Studies

Cable I_c measurements enabled estimates to be made of the extents to which I_c was degraded by:
(1) edge damage and (2) core-induced poisoning.

Study No.1, IGC-AS:
(a) The in-cable edge-to-edge $I_{c,4.2K,0T}$ of a single strand (195 A) was compared with that measured around the edge (164 A) -- a cabling-induced degradation of 16%.
(b) The full-cable $I_{c,4.2K,8T}$ of 646 A, was found to be about 49% of the sum of the individual-strand values for the same temperature and field, viz. 1260 A.

Combining these data it may be concluded that the presence of the core was responsible for a 35% decrease in $I_{c,4.2K,8T}$.

Study No. 2, SEWC:
The I_c of a sample of bare-core cable was compared with that of another whose core was protected by MgO paper. Whereas the latter carried an $I_{c,4.2K,0T}$ of 3495 A, the $I_{c,4.2K,0T}$ of the bare-core cable was only 2100 A -- a core-poisoning-induced reduction of 40%.

The agreement with the IGC-determined value of 35% is excellent.

CABLE PROPERTIES -- II

AC Coupling Loss and Interstrand Contact Resistance (ICR) Measurement

The goal of the AC-loss segment of the program was to explore the feasibility of winding a practical Bi:2212/Ag Rutherford cable with a coupling loss sufficiently low as to satisfy accelerator dipole (e.g. Large Hadron Collider, LHC, "inner" winding) requirements.

For coupling loss study the three special cables were wound at LBNL, each with a Nicrhome-80 (NC80) core.

(1) Cable **BI-NC** relied on just the self-oxidation of the NC80 core that took place during RHT
(2) In Cable **BI-AO-NC** the core was additionally protected by a plasma-sprayed coating of Al_2O_3.
(3) As an example of complete interstrand insulation, Cable **BI-NC-NC** was wound with alternating strands of Bi:2212/Ag and NC60 wire. Oxidation RHT of this cable gave it a "zebra-striped" appearance.

Coupling loss was expected for Cables BI-NC and BI-AO-NC, but none was expected (or found, hence ICR = ∞) for the fully insulated BI-NC-NC whose hysteretic-only loss enabled a correction to be applied to the measuring equipment.

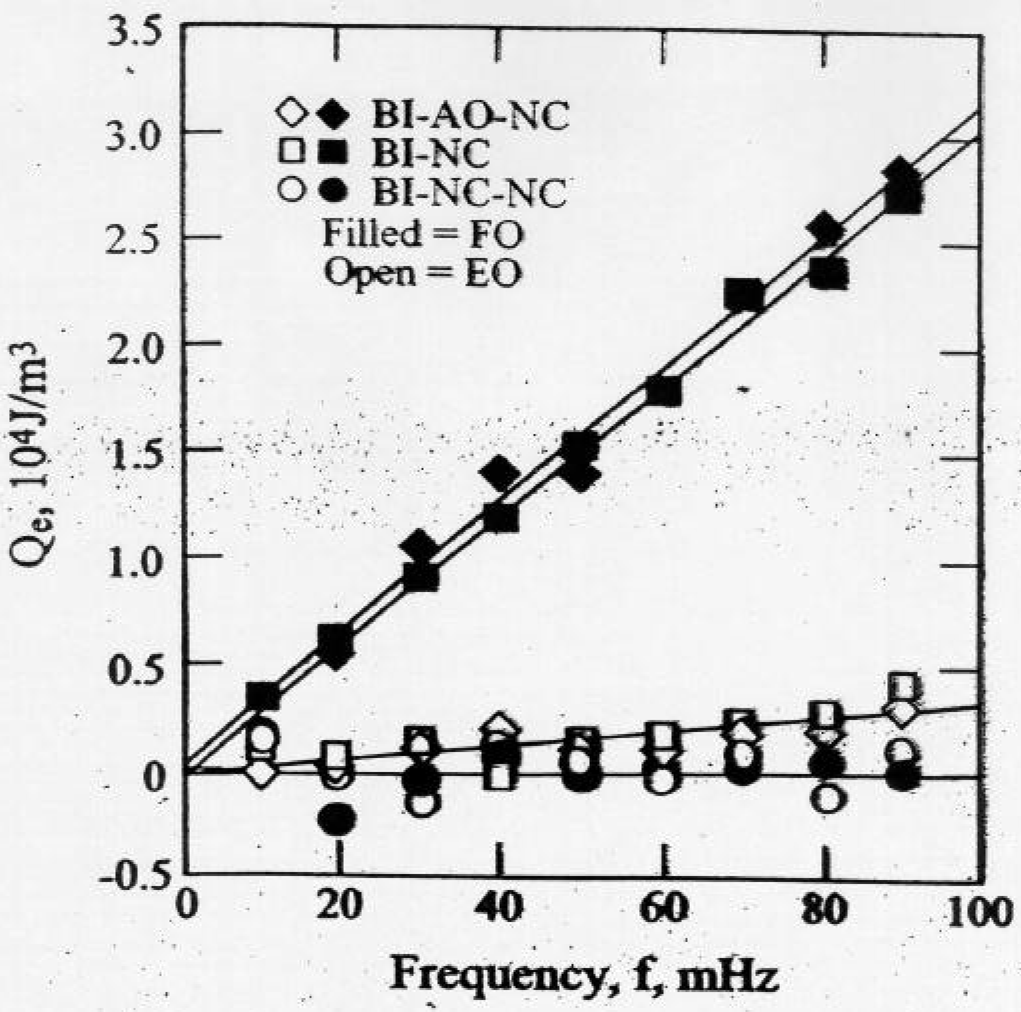


Fig. 1. **Coupling loss per cycle, Q_e, vs. field sweep frequency, f, at B_m = 400 mT, for the Bi:2212/Ag cables (after removal of the background slopes)**

CONTACT RESISTANCES

Cable Type	$R_{\perp}$, μΩ	$R_{\parallel}$, nΩ	$R_{\perp,eff}$, μΩ	$R_{\perp,eff.,LHC}$, μΩ
BI-NC	∞[a]	18.3	10.9	13
BI-AO-NC	∞[a]	17.9	8.7	10
BI-NC-NC	∞[a]	∞[a]	∞[a]	∞[a]

[a] The associated loss was not detectible.

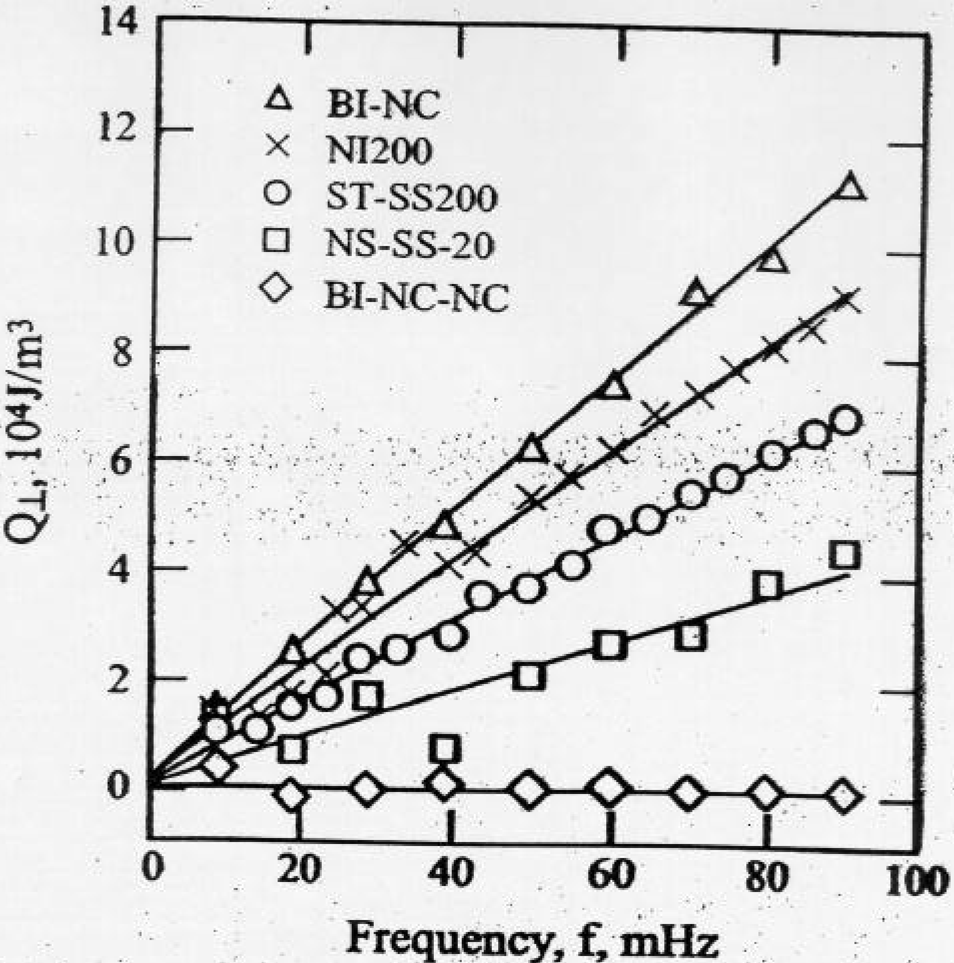


Fig. 2. **FO coupling loss, $Q_{\perp}$, normalized to LHC specifications vs. field sweep frequency, f, at B_m = 400 mT, for Bi:2212/Ag cables compared to cables NI200 (Ni-plated NbTi), ST-SS200 (stabrite-coated NbTi + SS core), and NS-SS-20 (bare Nb_3Sn + SS core).**

CONCLUSION

A National Laboratory, University, and Industrial collaboration has:

-- demonstrated the feasibility of winding a core-type Rutherford cable with Bi:2212/Ag strand with acceptable current carrying capacity

-- provided estimates of the extent of I_c degradation that results from winding-induced damage and poisoning from the Nichrome-80 core if unprotected by a suitable oxide coating, and offered a solution.

-- shown that results of model-cable AC loss measurements, extrapolated to the dimensions of an LHC-inner cable, yielded an effective FO ICR, $R_{\perp,eff.,LHC}$, of 10-13 μΩ which is close to a stated LHC target of 15 μΩ.